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Assessment of climate change impact on hydrological extremes in two source regions of the Nile River Basin

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Abstract

The potential impact of climate change was investigated on the hydrology and hydrological extremes of Nyando River and Lake Tana catchments, located in two source regions of the Nile River basin. Climate change scenarios were developed for rainfall and potential evapotranspiration (ETo), considering 17 different General Circulation Model (GCM) simulations to better understand the range of possible future change. Projected changes under two future emission scenarios for the 2050s were extracted from an ensemble of selected GCM experiments. The future climate change scenarios were constructed by transferring the extracted climate change signals to the observed series using a frequency perturbation downscaling approach, which accounts for the effect on rainfall and ETo extremes, its dependence on the return period of rain storm depth, and the correlation between rainfall and ETo changes. Two conceptual hydrological models were calibrated and used for the impact assessment. Their difference in simulating the flows under future climate scenarios was investigated. The results reveal that the hydrological models project increasing runoff extremes for Nyando catchment towards the 2050s while unclear trend is observed for Lake Tana catchment for cumulative volumes as well as high and low flows.

1 Introduction

Climate change impact studies associated with global warming as a result of greenhouse gases (GHG) has been given ample attention worldwide in the recent decades. Water resources ought to receive special concern as they are very vulnerable to change in climate and have a potential to be strongly impacted in their availability and quality (IPCC, 2007).

The Nile River is a water resource which is already under immense pressure due to various competitive uses as well as social, political and legislative conditions. On top of these, previous studies show that many parts of the Nile Basin are sensitive to climatic variations (Conway and Hulme, 1996; Yates and Strzeperk 1996, 1998a,b; Conway, 2005; Kim et al., 2008; Beyene et al., 2009) implying that climate change will have considerable impact on the resource. Therefore, it is necessary to analyse the possible changes in the different water resources aspects under the changing climatic conditions. However, due to variable climatic regions this impact might not be similar throughout the basin. Hence, dividing the basin into different regions will be a convincing and proficient approach when studying climate change impact.

Potential impact of climate change in the Nile Basin has been studied using outputs from General Circulation Models (GCMs) by different researchers on different catchments during the past years (Gleick, 1991; Conway and Hulme, 1993, 1996; Strzepek and Yates 1996; Conway 2005; Kim et al., 2008; Beyene et al., 2009). The studies used the approach of translating specified changes in climatic inputs into changes in hydrological regimes. However, they were limited by the coarse spatial resolution of the GCMs used and the small number of GCMs that could be evaluated (Beyene et al., 2009). In addition, the impact of using different hydrological models for a given climate change scenario is not widely investigated and reported in literature. The models, moreover, were not tested for their performance in describing/predicting extreme hydrological conditions. Projection of climate change impacts on hydrological extremes (floods, droughts, or water scarcity) is however of major importance for the region.

This paper investigates the potential impact of climate change on the hydrology and hydrological extremes for selected catchments of the Nile Basin. It considers the use of many GCM runs to provide a more complete range of uncertainty in the GCM based climate projections. Linking the coarse spatial resolution climate models with hydrological models requires downscaling techniques to provide catchment scale climate scenarios for rainfall and potential evapotranspiration (ETo) as input to hydrological models. In this paper, a frequency perturbation downscaling approach is used. This approach provides more reliable predictions as the climate change signals projected by the GCMs are realistically transferred to the observations through consideration of the change in wet days and wet day intensities for rainfall and intensities for ETo. The intensities were perturbed in relation to their frequency of occurrence. In this way, changes in high and low rainfall and ETo extremes, could be accounted for. Also the correlation between rainfall changes and ETo changes was considered.

1.1 Study area

Two catchments were selected, Nyando catchment in the Equatorial lakes region located in Western Kenya, and Lake Tana catchment, the source of Blue Nile, from the Ethiopian highlands.

Nyando catchment has a sub-humid climate with mean annual temperature of 23 °C and mean annual rainfall varying from 1000 mm near Lake Victoria to over 1600 mm in the highlands. The annual rainfall pattern shows no distinct dry season. It is tri-modal with peaks during the long rains (March–May) and short rains (October–December) with the third peak in August. The rainfall is controlled by the northward and southward movement of the Inter-Tropical Convergence Zone (ITCZ) (Muthusi et al., 2005).

The climate of Lake Tana is of "tropical highland monsoon" type with one rainy season between June and September and a dry season from October to March. The air temperature shows large diurnal but small seasonal changes with an annual average of 20 °C (Setegn et al., 2008). The seasonal distribution of rainfall is controlled by the northward and southward movement of the ITCZ. Moist air masses are driven from the Atlantic and Indian Oceans during summer (June–September). During the rest of the year the ITCZ shifts southwards and dry conditions persist in the region between October and May.

Although these two basins are classified under the sub-humid/humid climates, their rainfall patterns are rather different. For this reason this research attempts to ascertain the differences in climate change projections and consequently their potential impact on the hydrology of the two source regions of the Nile Basin: equatorial lakes region upstream of the White Nile and Lake Tana region upstream of the Blue Nile.

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2 Materials and methods

2.1 Hydrological modelling

The models used for simulating the river flows are lumped conceptual hydrological models, namely VHM and NAM calibrated individually for each catchment. VHM is a Dutch abbreviation for "generalized lumped conceptual and parsimonious model structure identification and calibration" following the procedure developed by Willems (2010). NAM is the Danish "Nedbør-Afstrømnings-Model", a lumped conceptual precipitation-runoff-model developed by DHI Water and Environment (DHI, 2008).

The VHM approach works through a step wise model structure identification procedure (Willems, 2010). The necessary input time series are rainfall and potential evapotranspiration averaged over the catchment. Prior to calibration it requires flow time series pre-processing, i.e. hydrological sub-flow separation (quick flow, interflow and slow flow), split of the time series in nearly independent quick and slow flow events, and extraction of nearly independent high and low flow extremes from historical flow records in the catchment. See Willems (2009) for more details on these time series processing techniques. From the rainfall, ETo and river flow time series, information is extracted that can be used to identify and calibrate the main hydrological catchment responses and storages. Storage elements are considered representing the surface, unsaturated zone and groundwater storage. These storages are combined with reservoir models to describe the routing of the sub-flows. Relations are identified between the rainfall fraction that per event contributes to the separated sub-flows and other hydrological variables. These relations represent sub-models describing soil storage, quick flow, interflow and slow flow volumes. The sub-model structure identifications and calibrations are done by matching the modelled fraction values with the ones estimated from the sub-flow filtering.

Similar to VHM the NAM model was set up with observed series of rainfall and ETo averaged over the catchments. In this case, the model structure was fixed, with three storage elements, surface, root zone and groundwater storages, and linear reservoir models describing overland, inter- and baseflow. Model parameters were determined by manual, trial-and-error calibration against the observations. For both VHM and NAM, model performance was evaluated and optimized by means of a multi-criteria model evaluation protocol included in the WETSPRO tool as described by Willems (2009). This model performance evaluation method includes a multi-objective set of goodness-of-fit statistics and complementary graphs.

Five years data (1976–1980) were used for calibration of Nyando river catchment and the period 1986–1990 for validation. Similarly, the period 1992–1995 was used for calibration of Lake Tana catchment and the period 1996–1998 for validation. The input rainfall and ETo data were calculated as weighted average time series from point measurements. Penman-Monteith method (Allen et al., 1998) was used for estimating ETo from observed maximum and minimum temperature in the catchments. For Nyando, the weighted average rainfall was calculated using 38 stations in and around the catchment, while four stations were used for the weighted average ETo computation (Fig. 1). In the case of Lake Tana catchment, five point stations were used to calculate both weighted average rainfall and ETo daily time series (Fig. 1). The availability of data determined the number of stations used for the analysis.

2.2 Developing climate scenarios

Developing climate change scenarios was performed using an ensemble of GCM simulations driven by two GHG emission scenarios, A1B and B1 of the SRES (Special Report on Emission Scenarios) of IPCC (2001) report. The period 1961–1990 was taken as the baseline scenario that represents the current condition, while the 2050s (2046–2065) were considered for the future climate scenario. Observed daily meteorological datasets were collected from the FRIEND/NILE database for Kisumu station representing the Nyando catchment and from the National Meteorological Services Agency in Ethiopia for Bahir Dar station representing the Lake Tana catchment.

It is assumed that models which simulate the present day climate well are more likely to also perform relatively well in simulating the future climate (Anderson et al., 2006). A consistency check between the GCMs and observed meteorological data

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was performed to assess each model's representativeness for the two catchments. The different GCM models were tested for their capacity to reproduce the reference (observed) climate for rainfall and temperature, which provided different assessments about model performance depending on the variable and test considered.

The meteorological variables with respect to which performance of the different GCMs was evaluated included: rainfall, maximum and minimum temperature. These variables were identified as relevant for hydrological impact assessment, with temperature data was used to estimate the baseline ETo using Penman-Monteith method. The models were selected based on the performance results from the statistical tests (root mean squared error and bias, as well as frequency analysis evaluation to assess the models' ability to simulate extreme events). Models found to consistently perform poorly in the different tests were excluded from the subsequent analysis. The method for this consistency check was similar to the approach by Baguis et al. (2010).

Expected climate changes in rainfall, temperature and ETo were determined as the ratio of the value in the scenario period to the value of the control period, known as perturbation factor. In case of rainfall, an approach based on frequency analysis of quantiles was applied where perturbation factors were obtained by comparing quantiles for given empirical return periods (or values of the same rank) in both the control and scenario series. This perturbation calculation was done using only wet days where a wet day was defined as a day receiving a minimum rainfall amount of 0.1 mm. Next to the quantile perturbation calculation for the wet day rainfall intensities, also changes in the wet day frequencies were calculated. For ETo, aggregated monthly totals were used instead of daily values as used in the rainfall analysis.

The changes extracted from the GCMs were probabilistically applied to the observed time series. The observed ETo series were perturbed by multiplying all values within a specific month by one factor. The observed rainfall series were perturbed first by removing or adding wet days in the series using a random procedure and secondly by applying intensity perturbation to each wet day dependent on the empirical return period (thus rank) of the rainfall intensity on that day.

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2.3 Impact analysis

After future scenarios were constructed for rainfall and ETo, the original and perturbed series were then used to drive the hydrological models for the two catchments in order to assess the influence of climate change. The hydrological models were run using control and future scenarios followed by statistical post processing of the hydrological simulation results. Changes in cumulative volume of flow in time (annual, seasonal and monthly), high and low flow extremes together with analysis of rainfall and evapotranspiration were estimated.

Regarding the extraction of the high flow peaks and the low flow minima from the time series the method of Willems (2009) was adopted where the peak over threshold (POT) selection was performed using three "independency" criteria. For low flows the method was applied after 1/Q transformation of the discharge series, where Q refers to the original discharge time series. This transformation changes the flow minima to maxima, which can be easily selected by POT analysis.

The results from the two models were compared for both the current and the future climate conditions. This helped to check the sensitivity of the results to the modelling technique selected. The regional difference between the two selected catchments was compared on their response to the climate change scenarios.

3 Results and discussion

The rainfall-runoff model calibration started with time series pre-processing of the available daily river flow series (Fig. 1) for both catchments. In a first step, the flow was separated in its runoff sub-flows based on the extended Chapman filter method described in Willems (2009). The Nyando river flow was separated into three components (slow flow, interflow and quick flow). In the case of Lake Tana catchment, the filtering was limited to only two components, the slow flow and quick flow components. In a second step, all significant peak and low flow events were extracted for both catchments. This

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involved separation of the flow series in nearly independent quick and slow flow periods (Willems, 2009) and selection of the maximum flow during each quick flow period (as peak flow event) and the minimum flow during each slow flow period (as low flow event).

The first and most important sub-model that needs identification and calibration in the VHM approach is the soil water storage model. The appropriate storage model was evaluated by plotting the storage fraction of precipitation versus the soil water state as in Fig. 2. For both catchments, the exponential model, which has a mathematical relation as Eq. (1), gave good results. The soil moisture storage volume is emptied by the actual evapotranspiration which is the fraction of potential evapotranspiration. The actual evapotranspiration is modelled as a linear relation as per Eqs. (2) and (3).

$$f_u = c_1 - \exp\left(c_2 \left(\frac{u}{u_{\max}}\right)^{c_3}\right) \quad (1)$$

where:
u is soil water depth
$u_{\max}$ is maximum soil water capacity
c_1, c_2 and c_3 are model coefficients
f_u is rainfall fraction to soil water storage

$$e_a = e_p \quad (u > u_{evap}) \quad (2)$$

$$e_a = \frac{u}{u_{evap}} e_p \quad (u \leq u_{evap}) \quad (3)$$

where:
e_a is actual evapotranspiration
e_p is potential evapotranspiration
u_{evap} is threshold value for u, above which e_a becomes equal to e_p

Figure 2 is constructed after calculation of the storage fraction of precipitation per slow flow event as the rest fraction after subtraction of the runoff subflow filter fractions

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from the total precipitation depth, and after subtraction of the actual evapotranspiration. Each point in the figures represents one slow flow event ("filtered" based on observations and filter results; "modelled" after model simulation).

Depending on the soil storage results, quick flow and interflow fractions of precipitation were analyzed. Exponential models were identified for both catchments which have mathematical relations as Eq. (4). The model performance was evaluated by visual judgements as well as statistical indicators such as Nash-Sutcliffe coefficient (NSE) and water balance discrepancy (WBD). Similar evaluation was done for the NAM model results. Table 1 gives a summary of the statistical comparison. The findings show that the capacity of reproducing the historical time series by the hydrological models is similar and almost equally well for both catchments. Moreover, the models were evaluated for their ability to predict more extreme conditions for both peak and low flows. The performance of the model is graphically illustrated in Fig. 3. The graphs show that the VHM model has better simulation capacity than the NAM model in terms of extreme flows as its results are closer to the historical observations. VHM model results therefore were given higher credibility when analyzing the impact assessment on the extremes.

$$f_{i,o} = \exp\left(\left(c_1 + c_2\frac{u}{u_{max}}\right) + (c_3 + c_4 \ln r)\right) \quad (4)$$

where:

r is antecedent rainfall (previous day)

c_1, c_2, c_3 and c_4 are model coefficients

$f_{i,o}$ is rainfall fraction to interflow or overland flow

3.1 GCMs performance

In total, results of 28 runs with 17 GCMs and two GHG emission scenarios (A1B and B1) have been obtained from the IPCC AR4 Archive for the grid cells covering the study areas. For each of these runs, error and bias tests were performed in annual, seasonal and monthly aggregation levels for both rainfall and temperature. In addition, quantile/frequency analysis was used to assess the ability of the models to simulate extreme events. These different statistical tests on GCMs performance to simulate historical records of climatic variables show generally better simulation results for temperature than rainfall. This result is expected as rainfall is naturally less predictable. The poor simulation result of GCMs for precipitation is also due to their failure to simulate the seasonal migration of the ITCZ in these equatorial regions (Wu et al., 2003).

Generally, the historical rainfall is better simulated by the GCMs for Nyando than Lake Tana catchment. The poor simulation for Lake Tana catchment is attributed to both the topography and the complex climate system. Given the coarse resolution of GCMs the change in topography is most probably not adequately modelled. On the other hand the summer (JJA) rainfall in the catchment is influenced by monsoon activity (Beyene et al., 2009), which might not be accurately considered by the GCMs.

No particular GCM run performed consistently well at all timescales, either for all tests or for both variables and catchments. Therefore, the performance of a GCM run is basin specific. However, there is better convergence among the GCM runs in the Nyando catchment (Lake Victoria area) than in the Lake Tana catchment (Blue Nile area), similarly to what was found by Hulme et al. (2001) and IPCC (2001).

3.2 Nyando catchment response

The 20 year period 1971–1990, was used as baseline control period to run the hydrological models and to be compared with the 2050s (2046–2065) future scenarios. The changes in the annual mean flow from different scenarios by 2050s gave a wide range of results. For mean annual rainfall changes between −10% and 31%, the mean annual flow ranges from −27% to 118% using VHM simulations while it ranges from −34% to 149% using NAM. This range of change implies that the climate change impact is highly uncertain. Wider variations are observed between the rainfall projections than between the evapotranspiration projections. Consequently, the large impact range is explained mainly by the considerable uncertainty in the rainfall projections. Change

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in evapotranspiration ranges from −6% to 9%. These change results are comparable with another research conducted for the Nzoia River in Kenya based on monthly data (Githui et al., 2009). In that study, mean annual rainfall values were found to change between 2.4% and 23.2%, corresponding to stream flow changes in the range from 6% to 115%. The research, however, used limited number of GCM runs.

Similar to the annual mean flow change, the seasonal analysis showed wide and varied magnitude of change for the different seasons. However, most of the GCMs projected increase in the river flow across all seasons as the calculated perturbation factor is greater than one in most of the cases.

Extreme peak flows of Nyando River until the 2050s generally tend to increase (Fig. 4). The projected changes in low flows show both increases and decreases of the flow values from the control period (Fig. 4). Table 2 shows the range of change for the different GCM runs as function of return period. The projected increase in the peak flows would increase the number and extent of flooding events in the catchment. This is of major concern as this area has records of damage due to severe flooding experience in the past.

3.3 Lake Tana catchment response

In case of the Lake Tana catchment the period 1990–2000 (11 years of data) was used as baseline control period to run the hydrological models. Comparing it with the 2050s future scenarios, the mean annual outflow change ranges from −72% to 75% using VHM and −81% to 68% using the NAM model. This wide impact in the outflow is explained by considerable change in climate variables, mainly precipitation. The precipitation projections cover a broader range than the evapotranspiration projections; similar to what has been found for Nyando. The range of change in precipitation and ETo are from −30% to 18% and from 1% to 8%, respectively. The two hydrological models agree in their outflow impacts; the sign and order of magnitude of flow change are indeed similar.

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The result of the seasonal analysis is described in Fig. 5. Similar to the annual analysis the models gave a wide range of impact result showing both significant decreases as well as increases in the outflow across the seasons. It is therefore highly uncertain either to expect increase or decrease in the outflow for the 2050s. Approximately half of the GCM runs project flow increases and the other half project decreases.

Similar to the annual and seasonal analysis the projected extreme flow results have a wide range. This creates uncertainty on whether to expect higher or lower peak and low flows. The range of possible projections was summarized in terms of highest, mean and lowest impacts. The average percentage change of peak flows for the highest, mean and lowest impacts are +79%, +10% and −31%, respectively. Similar analysis for the low flows gave +56%, +12% and −61% for highest, mean and lowest impacts, respectively.

3.4 Regional difference

Though the period used for the two catchments and the number of GCM runs considered was not the same, general comparison was made using the GCM runs that were common for both catchments. The projected change in annual mean flow using four GCMs for both catchments is as shown in Fig. 6. This result illustrates that for the 2050s the flow in Nyando catchment will likely increase more than for the outflow of Lake Tana catchment. In Fig. 6, the impact differences between A1B and B1 emission scenarios are also shown.

4 Conclusions

This study aimed at achieving two goals: studying the climate change impacts on Nyando and Lake Tana catchments, which are two representative source regions for the White and Blue Nile Basins, respectively, and investigating hydrological impact uncertainties. It made use of evaluated GCM runs (17 GCMs in total, for A1B and

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B1 GHG emission scenarios) to develop and construct an ensemble set of climate change scenarios for hydrological impact assessment. The impact assessment was performed based on NAM and VHM lumped conceptual hydrological models. During calibration and validation of these models, specific focus was given to the hydrological extremes (high and low flows). Also the impact assessment specifically focused on these extremes, next to annual and seasonal flow volumes.

The findings of this paper can be summarized as:

- The capacity of reproducing historical time series by the hydrological models is similar and almost equally well for both catchments.
- The GCMs show wide range of ability to simulate rainfall, maximum and minimum temperature. In addition, clear variation is observed on the obtained climate change signal according to the GCM and emission scenario considered. It shows that climate change impact assessment based on only few climate models and emission scenarios does not make sense. It would largely underestimate the climate change uncertainty. Instead, an ensemble approach as applied in this study is advisable.
- Climate change impact according to the GCMs projection is different for the two catchments with considerable uncertainty. This uncertainty is mainly the result of varied precipitation projections by the GCMs.
- The findings from the two lumped conceptual hydrological models illustrate that the range of percentage change is in similar order of magnitude and sign. Therefore, the hydrological uncertainties have little influence on the future climate change results of these catchments compared to the uncertainty in the GCM results.
- Considering the impact results based on the GCM runs used, Nyando River catchment shows increasing flow trends until the 2050s. Given that at present

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this catchment is already prone to flood related socio-economic consequences, these trends are of major concern. Lake Tana catchment, however, shows unclear trends, neither increasing nor decreasing outflow trend, as half of the GCM runs project increases and the other half project decreases of its outflow.

Overall, the range of projections obtained in this research is much wider than in previous studies. This is due to the wider range of the numerous GCM runs used. The uncertainties related to the precipitation projection of GCMs suggest the necessity of improvements on the climate models. Moreover, the use of Regional Climate Models (RCMs) would be better for hydrological impact studies as their spatial resolution is less coarse than the GCMs. RCMs would indeed enable better coverage of topographical variations across the catchments. Also the accuracy of the ITCZ movement modelling needs to be improved.

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Table 1. VHM and NAM model performance in simulating the historical records for calibration period.

Calibration	Nyando		Lake Tana	
	VHM	NAM	VHM	NAM
NSE	0.4	0.46	0.88	0.75
WBD	+7%	−7%	15%	−27%

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Table 2. Factor change in peak/low flow extremes for Nyando catchment and specific return periods.

Return Period (years)	Range of change (change factor)	
	Peak flows	Low flows
1	1.0–2.4	0.7–1.8
2	1.1–2.4	0.8–1.4
5	1.1–2.6	0.5–1.5
10	1.2–3.8	0.9–1.8

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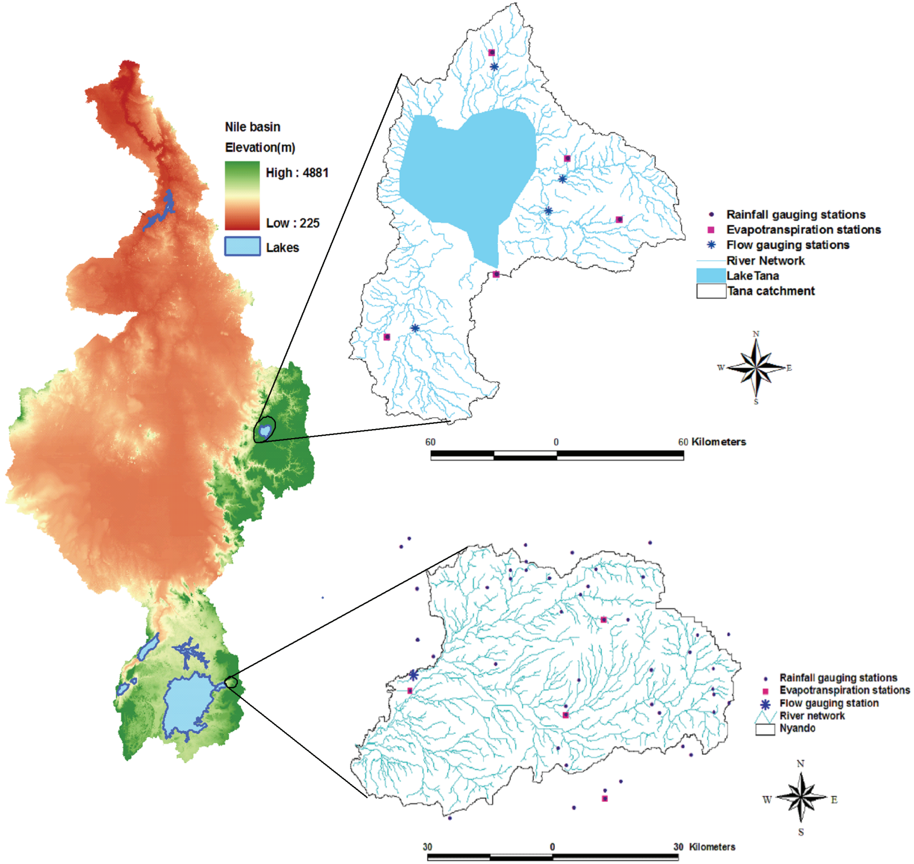

Fig. 1. The Nile Basin (left) and Meteorological and flow gauging stations in Lake Tana catchment (top, right) and Nyando catchment (bottom, right).

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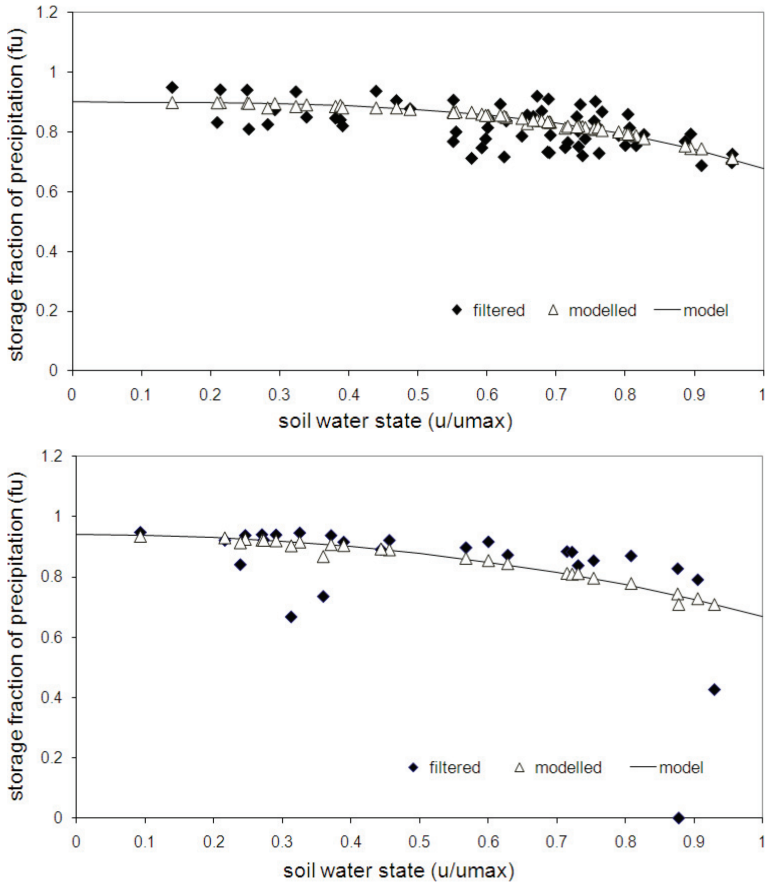

Fig. 2. Identified and calibrated soil water storage model for Nyando catchment (top) Lake Tana catchment (bottom).

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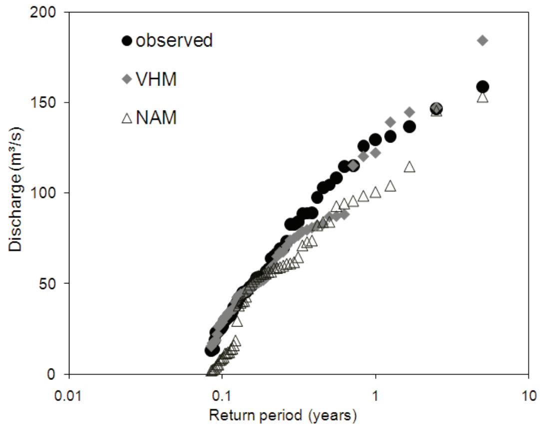

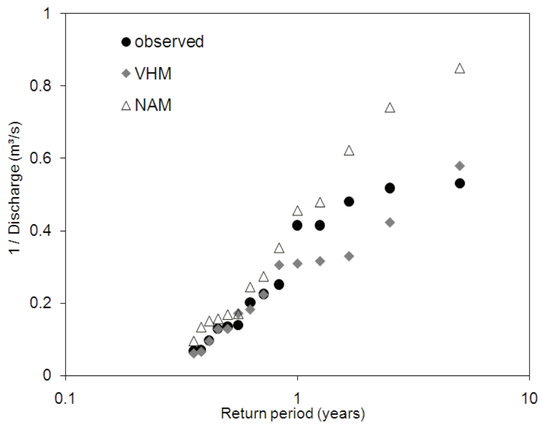

Fig. 3. Return period of daily peak flow extremes (top) and low flow extremes (bottom) for Nyando catchment: comparison of observations with model results during calibration period (1976–1980).

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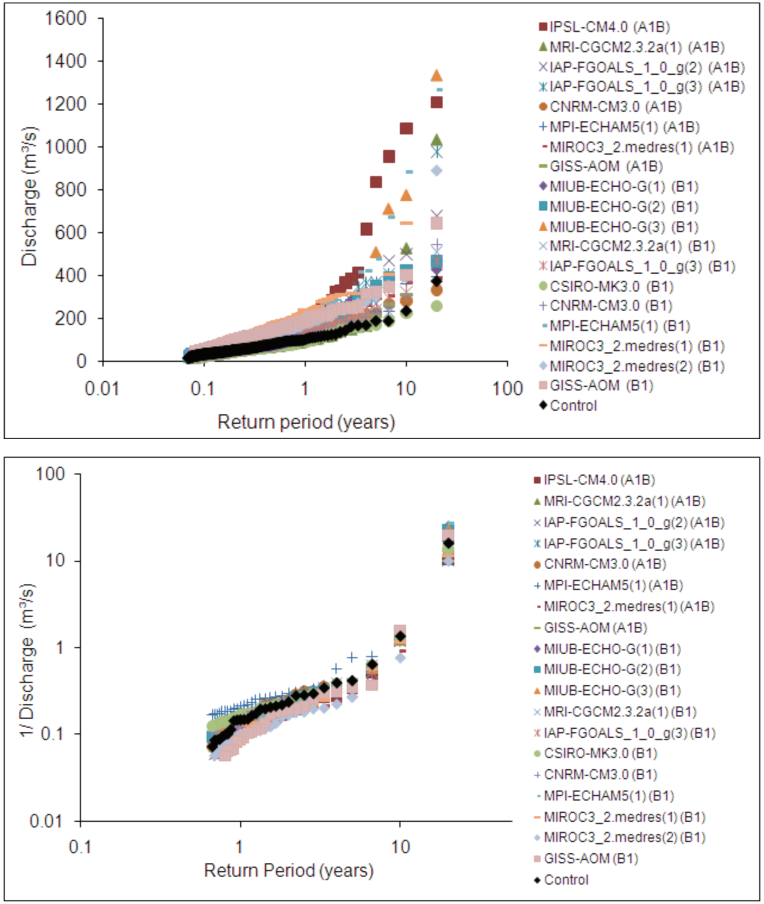

Fig. 4. Return period of daily peak flow extremes (top) and low flow extremes (bottom) for Nyando catchment, for control period (1961–1990) and future period (2046–2065) based on different GCM runs.

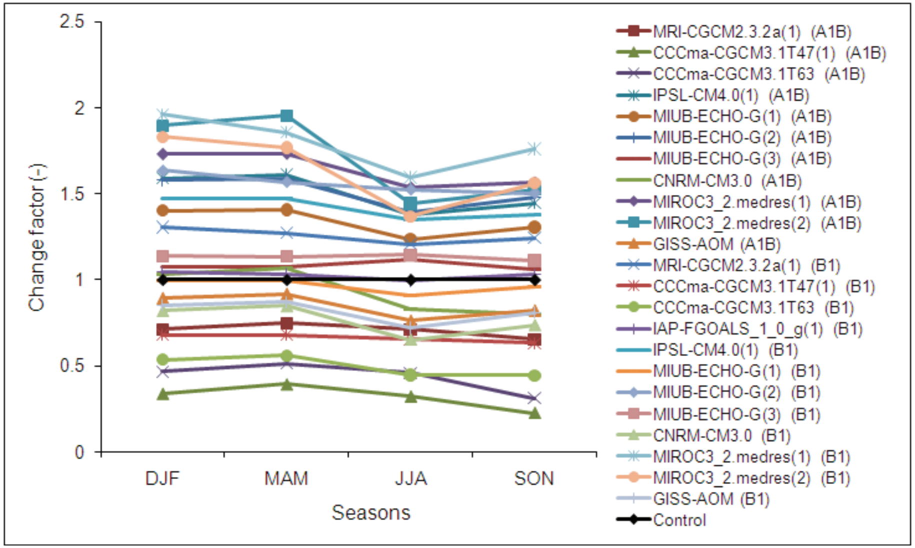

Fig. 5. Projected seasonal mean flow change of Lake Tana for 2050s.

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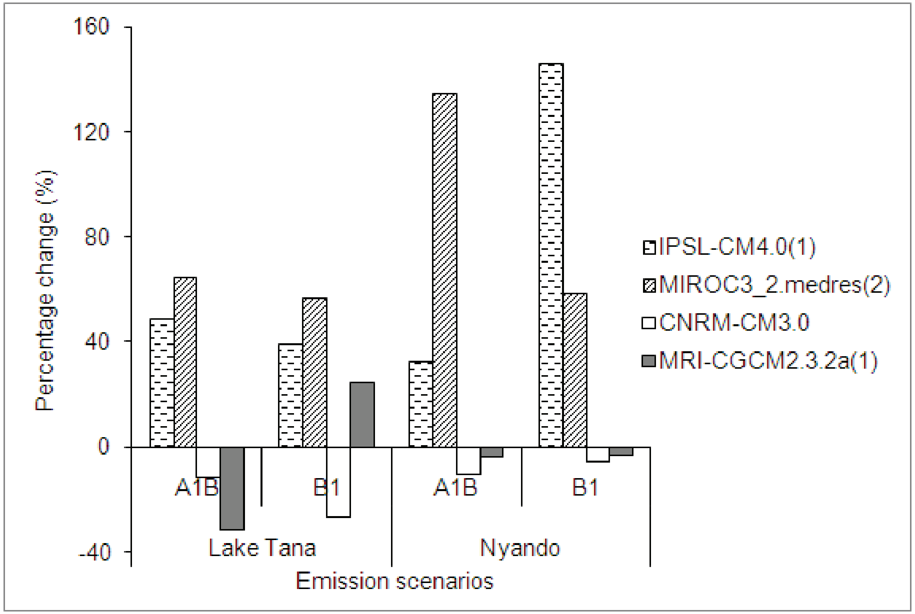

Fig. 6. Regional projected change comparison of mean annual flow volumes between Nyando and Lake Tana catchments for eight GCM runs.

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